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DIAGNOSTICS FOR LOW INTENSITY BEAMS

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Abstract

With the advent of the antiproton project, in 1976, one was confronted at CERN with the task of measuring beams of intensities significantly lower than usual until then. Some years later, a further need to deal with low-intensity beams arose, when ion-beams were introduced, first oxygen, then sulfur, and finally lead. This report highlights some of the solutions found for these tasks.

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DIAGNOSTICS FOR LOW INTENSITY BEAMS

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INTRODUCTION

There is no established definition of "low intensity", it is all relative, has different meanings at different machines and depends on the context.

At CERN, it was with the advent of the antiproton project, in 1976, that one was confronted with the task of measuring beams of intensities significantly lower than usual until then. Some years later, a further need to deal with low-intensity beams arose, when ion-beams were introduced, first oxygen, then sulphur, and finally lead.

In most cases, existing kinds of instruments were extended downward in their range, sometimes simply by adapting the front-end electronics, sometimes by more radical changes to the design. A novel type of instrument was the Schottky-pickup, also in a resonant variant. To measure the antiprotons, ultra-slow-extracted from LEAR and distributed to several simultaneous users, was a particular challenge.

This report highlights, in the form of case histories, some of the solutions for the above-mentioned tasks, in a more general way. Practical examples with detailed data are given in the companion-report by J. Bosser [1].

LOW-INTENSITY BEAMS OF THE ANTIPROTON PROJECT

The overture to the Antiproton Project was the ICE (Initial Cooling Experiment) storage ring. It was built in 1977 in a record-time of 9 months from the magnets of a muon storage ring, other surplus or borrowed components, and some quickly built new equipment. It was to test the validity of the two keys to antiproton accumulation, stochastic and electron cooling [3]. Protons of about 2 GeV/c were injected from the 26 GeV PS. Their intensity was only a few 10^9 in a single bunch, because of limitations in the transfer line and to keep radiation levels low.

For the closed orbit measurement, to have a sufficient signal level, electrostatic pickups were chosen, with high-input-impedance preamplifiers connected directly to the vacuum feedthroughs [2]. This technique proved highly successful and was subsequently used in all other antiproton machines: the Antiproton Accumulator (AA), LEAR, and the Antiproton Collector (AC).

The Q-value was determined by carefully counting transverse oscillations on Polaroid pictures. The result was accurate to a few 0.001.

With 74 m circumference and $\beta = 0.913$, 10^9 protons correspond to 590 μA. The resolution achieved at that time with dc beam transformers, of the magnetic amplifier type, was about 10 μA, adequate for the usual machine experiments, but not for observation during cooling experiments, with only some 10^7 protons. Intensities many orders of magnitude below the reach of the beam transformer were measured with a Schottky-pickup, of the wall-current type, and a spectrum analyzer set to a high harmonic of the revolution frequency. This was calibrated against the beam transformer at 100 μA, where its accuracy was still 10% .

Schottky intensity measurements were pushed to the limit during an experiment to measure the lifetime of the antiproton [4]. In a rather artistic way, the poor flow of antiprotons from a target in the ICE injection line was accumulated into stacks of a few 100 antiprotons. The beam was then cooled to a momentum spread of a few 10^{-5}. The resulting small frequency spread permitted narrow-band observation, using as Schottky-pickup a cavity of Q=5000, tuned to the 35th revolution harmonic. Its signal was averaged over several minutes. At the beginning of the experiment, there were 240 antiprotons, 85 h later 80 were left (Fig. 1). This established a lower limit for the lifetime of the antiproton, at rest, of 32 h, 9 orders of magnitude above the previous experimental limit. The resolution of the intensity measurement was estimated at ± 13 antiprotons, a still unbroken world record for circulating hadron beams.

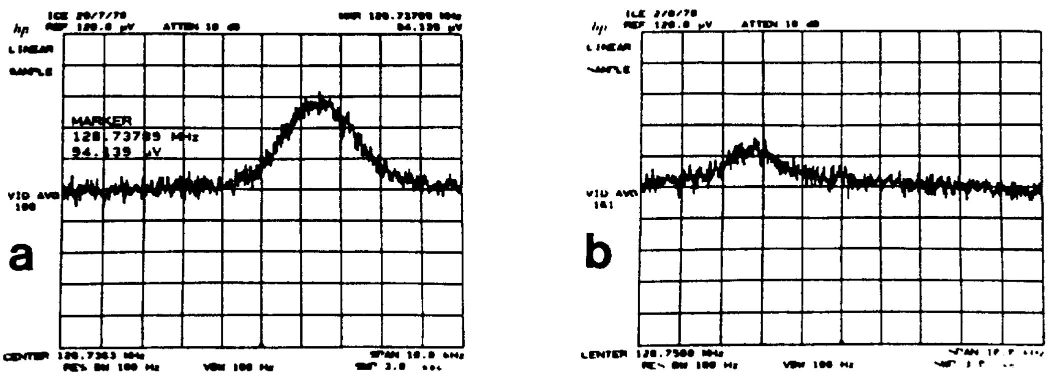

Fig. 1: Schottky scans made during the antiproton lifetime experiment at ICE.
a) At the beginning: 240 antiprotons. b) 85 hours later: the remaining 80 antiprotons.

It is interesting to note that for electrons the record-resolution to a single one was established much earlier, in 1961, by measuring the beam's synchrotron radiation, on the storage ring ADA in Frascati [5], a feat repeated later at several other electron storage rings.

Another remarkable achievement in ICE was the measurement of transverse profiles, indispensable in proving stochastic cooling of betatron amplitudes. Ionization electrons from the rest gas were extracted by an electrostatic field onto a scintillator layer on the inside of a window. The light from it was scanned with a rotating drum with a slit on its circumference and a photomultiplier at its centre. With a beam of $6 \cdot 10^9$ protons and a vacuum of $3 \cdot 10^{-9}$ Torr, good profiles were obtained [6].

ICE was followed by the AA, started up in 1980. The AA is set up with test beams from the PS, some 10^{10} protons of 3.5 GeV/c. In the beginning, several 10^6 antiprotons were injected every 4.8 s and stacks of up to $1.3 \cdot 10^{12}$ antiprotons have been accumulated. Of the many diagnostic systems, only few shall be mentioned.

As for ICE, electrostatic pickups were chosen, with high-input-impedance preamplifiers at a few cm from the feedthroughs. Due to the particular optics of the AA, the pickups were up to 70 cm wide and beam position had to be measured accurately far from the centre. In fact, a resolution and reproducibility of 0.2 mm was achieved [7].

The dc beam transformer, of the magnetic amplifier type, has a resolution of about 3 µA, corresponding to 10^6 particles. Remarkably, it is virtually free of drift: its zero-point shifts by about 3 µA, whether one observes it over a few minutes, a few hours, or even a month. In this respect, it is unique, no later specimen ever equaled it. Its resolution and steadiness permit an accurate measurement of the AA acceptance: blowing up a test beam until heavy losses occur, then carefully advancing a scraper until the beam transformer shows a loss of $2 \cdot 10^6$ protons, one finds the 99.8% emittance of a beam filling the aperture, i.e. the machine's acceptance.

Needless to say, Schottky signals are widely used to measure a variety of beam parameters. For intensity measurements, they are calibrated against the beam transformer and permit a resolution of 10^4 particles. For emittance measurements, their indication of the rms betatron amplitude is calibrated against the mechanical scrapers.

More is said about the later machines, AC and LEAR, in J. Bosser's paper [1]. As for the diagnostics in the SPS proton-antiproton collider, we refer to [8]. Let us just underline the single-shot character of the antiproton transfers between all these machines (a bunch every hour, even only once a day) and the resulting obligations for the diagnostic systems.

LOW-INTENSITY ION-BEAMS

The history of ion-acceleration at CERN and the present lead-ion facility are described in [9]. Much new diagnostic systems had of course to be provided for the new ion-source, RFQ and linac. Some systems in the Booster and the PS were able to cope with the meagre ion intensities, others had to be improved. We shall mention the two which were of prime importance, scintillator screens and secondary emission (SEM) grids. Both are based on the energy loss of particles in matter. In the Bethe-formula (here in Gaussian units) we see where we gain when dealing with ions:

$$\frac{dE}{ds} = 4\pi ZN \frac{z^2 e^4}{m\beta^2 c^2}\left[ln \frac{2m\gamma^2\beta^2c^2}{I} - \beta^2 \right]$$

m electron mass; e elementary charge; c velocity of light
beam particle: dE/ds energy loss per unit length; z charge number; ß, γ relativistic parameters
traversed material: N atoms/cm^3; Z atomic number; I ionization potential.

Firstly, dE/ds is proportional to the square of the particle charge z. This means that per particle charge we obtain z times more light or secondary electrons, a particular advantage with Pb^{82+} ions. Secondly, when the ions are not yet fully stripped at low energies, this is partially compensated by the fact that dE/ds is proportional to $1/\beta^2$, i.e. greater at low energy.

Scintillator screens, made from chromium-doped alumina, bearing a graticule and observed with a TV camera, were the prime means in threading the ion beams through transport lines and accelerators. E.g. in the Booster injection line, densities of a few 10^7 Pb^{53+} ions per cm^2, at 17 MeV/u, are still observable.

SEM-grids were used at the lead-linac for profile measurement and spectroscopy. After ejection from the PS at 4.25 GeV/u, they provide the ultimate quality control before delivery to the SPS. Their sensitivity is a few nA per ribbon or wire. Already with the weak oxygen and sulphur beams, many years ago, they were able to deliver decent profiles. Present-day beams of a few 10^8 lead-ions, i.e. a few 10^{10} charges, are an easy object.

STATISTICAL LIMIT

To conclude, we touch upon a fact of life in measurements at low intensities.

Extending the range of measurement systems to lower beam intensities means lower input signals, and, in the first instance, requires improvement of the signal-to-noise ratio. A careful analysis needs to be made of the various sources of noise, and an overall optimisation [10].

However, as one reduces the noise level and increases the gain of a system, pushing the sensitivity ever further, one will finally meet the inexorable statistical limit. As one approaches it, one is forced to hit a compromise between accuracy, spatial resolution and time resolution.

Let us look at it through the example of transverse density profiles. These are often measured by collecting electrons or photons, produced by the beam's particles in a gas, from a foil or in a scintillator. The collection occurs into channels, the width of which is given either by the design, as in the case of a SEM grid, or by the spatial resolution of the device.

Let us assume that the projection of the beam's 2-dimensional density distribution onto one plane has a Gaussian shape (Fig. 2), with σ the standard deviation or rms-width.

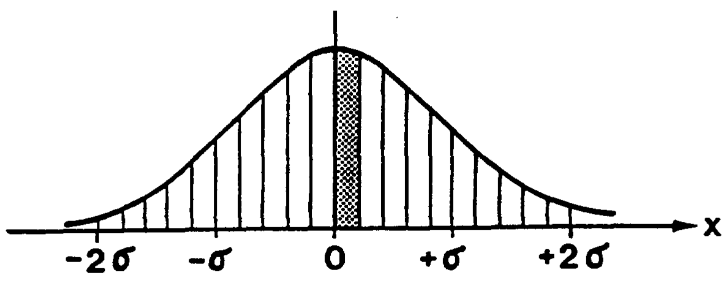

Fig. 2: Distribution of a Gaussian profile over channels 0.2σ wide

Within a time interval, which may be the desired measurement time, or simply the time that the beam lasts, the total number of electrons reaching the detector is N_{tot}. Let us take a channel width of $dx = 0.2\sigma$. The 20 channels between $x = -2\sigma$ and $x = +2\sigma$ will collect $0.95N_{tot}$ electrons. The number collected on a central channel, from $x = 0$ to $x = 0.2\sigma$ is

$$N_C = 0.083\ N_{tot}.$$

The statistical fluctuation on N_C is $\sqrt{N_C}$ and is also called "sampling fluctuation". Let us demand a 5% accuracy on the central channel, then

$$\sqrt{N_C}\,/\,N_C = 0.05 \quad \text{therefore} \quad N_C = 400$$

Since $N_C = 0.083\ N_{tot}$, we need for a "good" profile

$$N_{tot} = 4800 \text{ electrons}$$

In this analysis we considered as determining the number of electrons or photons stemming from the primary generation process, assuming their number to be much smaller than that of the beam particles which created them. In case of a production multiplicity >>1, the analysis must be based rather on the number of beam particles involved.

In fact, when the first rather weak lead-ion beams, ejected from the PS, were observed with SEM grids, statistical fluctuations were apparent in the profiles.

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